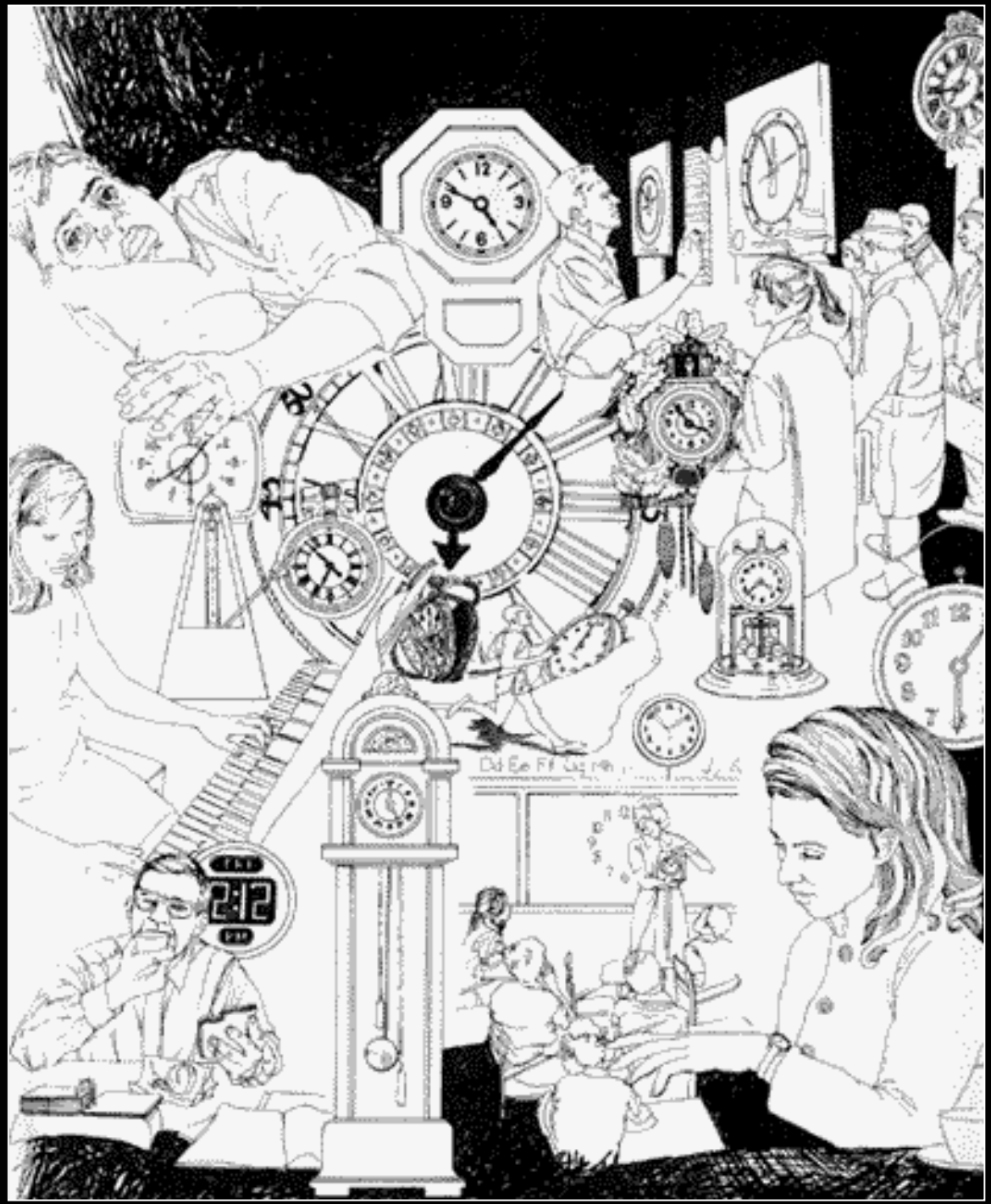


Lecture 17
June1, 2004

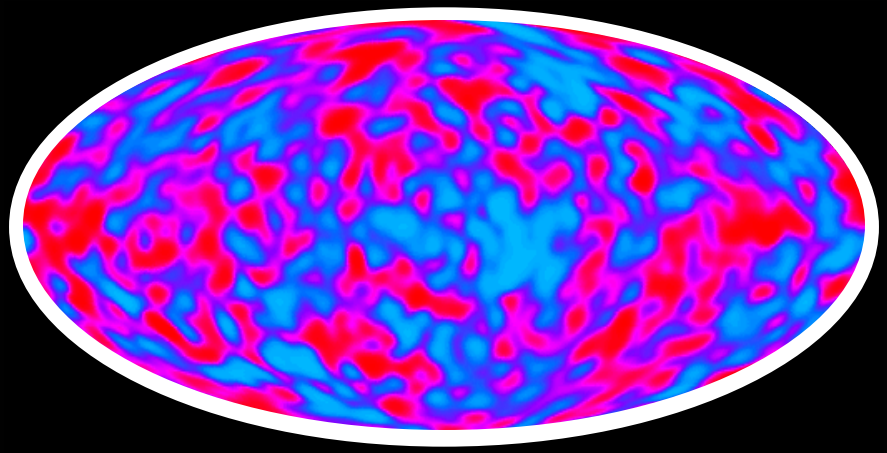
The Last Lecture

It's about time!

News of the week

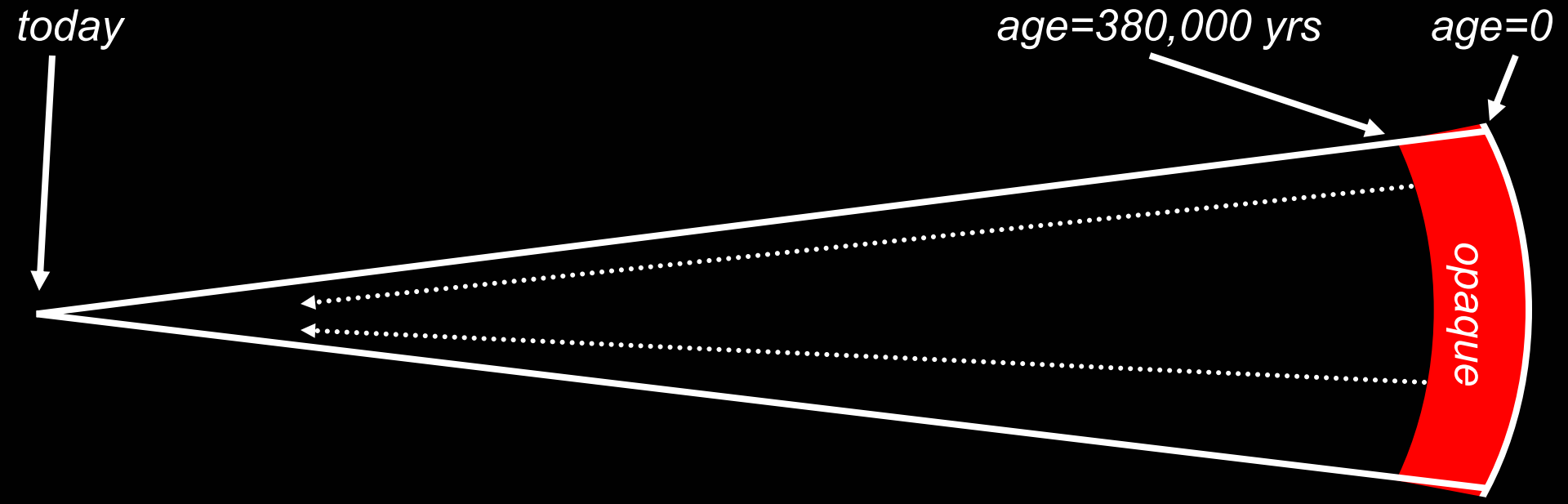
- **No more homeworks!**
- **No labs this week!**
- **Final Exam: Tuesday, June 8th, 10:30am-12:30pm**

Primordial perturbations

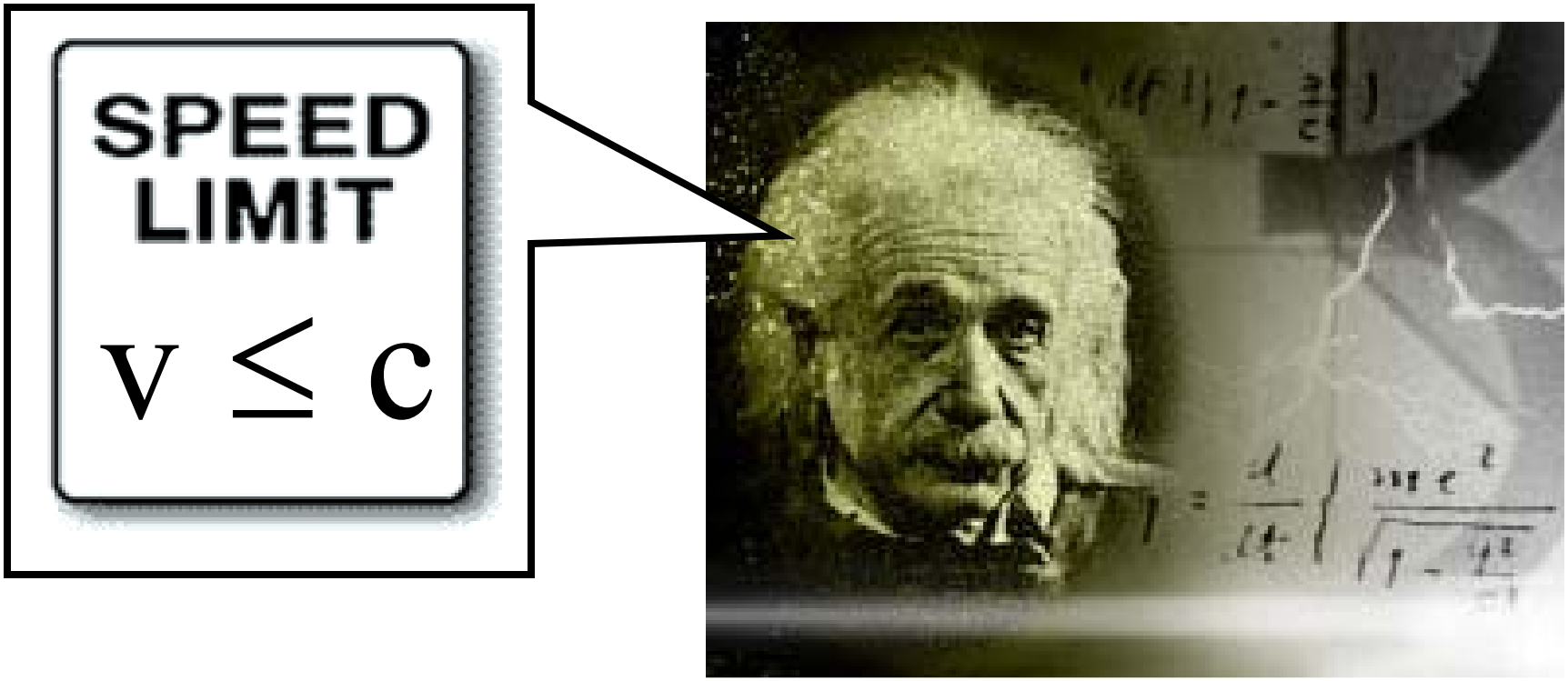


CBR: a snapshot of the universe 380,000 years AB

correlations on scales $\gg$ 380,000 light years



More than 380,000 light years in less than 380,000 years?



- $v \leq c$ for velocity *through* space
- no limit on expansion velocity *of* space
- requires “inflation”
  (accelerated expansion-negative pressure)

Nothing changes!

Today: dark energy (the vacuum, empty space)

0.000 000 000 000 000 000 000 000 000 001 g cm^{-3}

Inflation: dark energy (the vacuum, empty space)

1.000 000 000 000 000 000 000 000 000 000 000 000 000 000 000 000 000 000 000 000 000 000 000 000 000 000 000 000 000 g cm^{-3}

Cosmic Symphony (Harmonice Mundi)

expansion tempo	movement	epoch	relic
pizzicato	string	10^{-43} s?	???
presto	inflation	10^{-35} s?	CBR fluctuations gravitational waves seeds of structure
allegro	radiation	earlier than 10,000 years	abundances of the light elements
andante	matter	later than 10,000 years	growth of structure: galaxies, clusters,…
largo	inflation	day before yesterday	acceleration of the universe

“For every complex natural phenomenon there is a simple, elegant, compelling, wrong explanation.”

- Tommy Gold

An early particle cosmologist

Erwin Schrödinger

1938-1939: Graz → Vatican → Gent, Belgium → Dublin

The proper vibrations of the expanding universe

Erwin Schrödinger (1939)

Introduction:

production of matter, merely by expansion [of the universe],… Alarmed by these prospects, I have examined the matter in more detail."

Conclusion:

"… There will be a mutual adulteration of [particles] in the course of time, giving rise to … the 'alarming phenomenon'…"

The proper vibrations of the expanding universe

Erwin Schrödinger (1939)

Creation of a *single* pair of particles

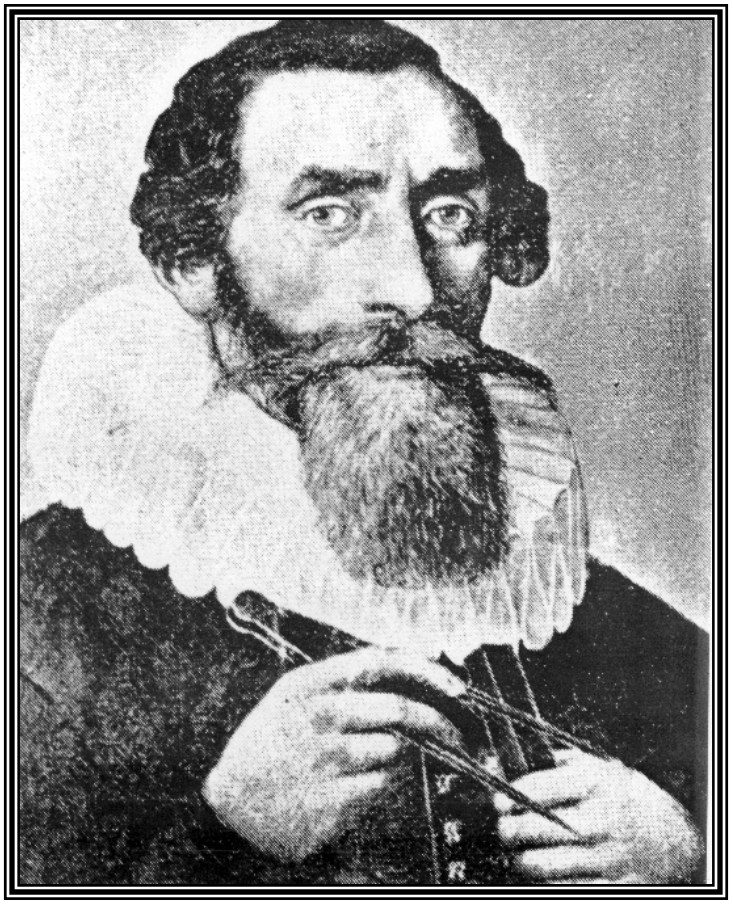
of undetectably small energy

somewhere in the universe

in the next 14 billion years

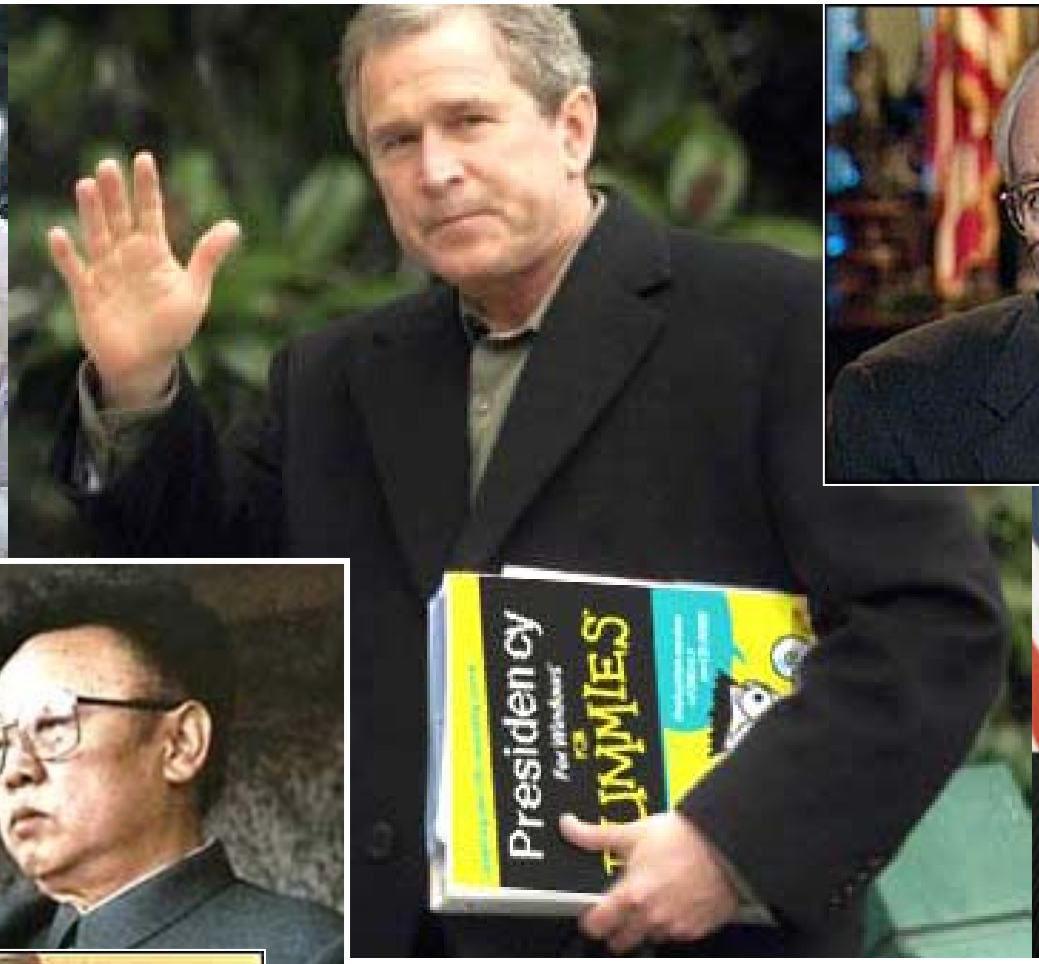
Alarming?

An even earlier Graz cosmologist



"When the storms rage around us, and the state is threatened by shipwreck, we can do nothing nobler than to lower the anchor of our peaceful studies in the ground of eternity." - *J. Kepler*

1600-1630: Graz → Prague → Linz → Sagan → Ratisbon

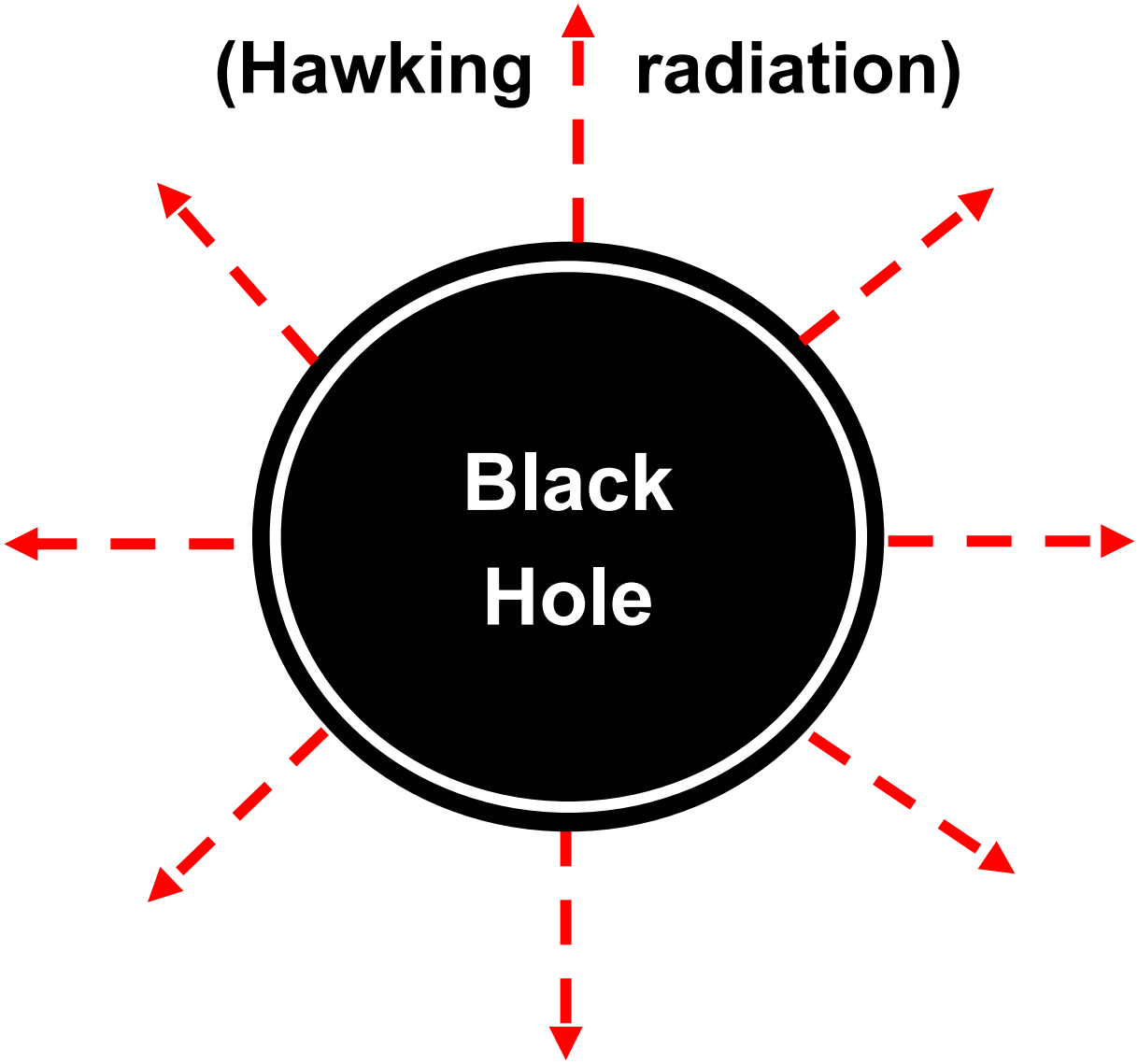


"When the storms rage around us, and the state is threatened by shipwreck, we can do nothing nobler than to lower the anchor of our peaceful studies in the ground of eternity."

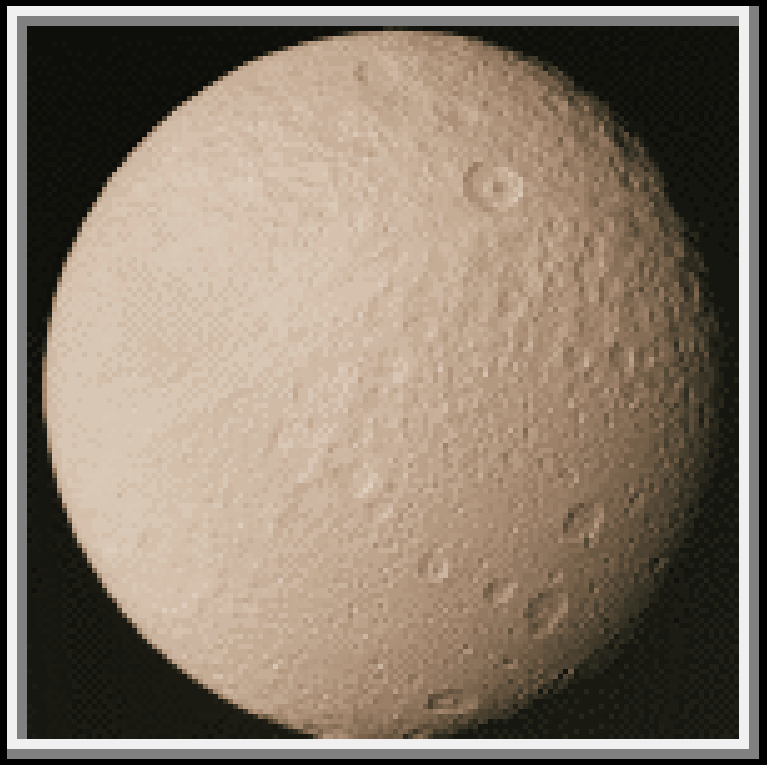
Disturbing the vacuum

Strong gravitational field → particle production

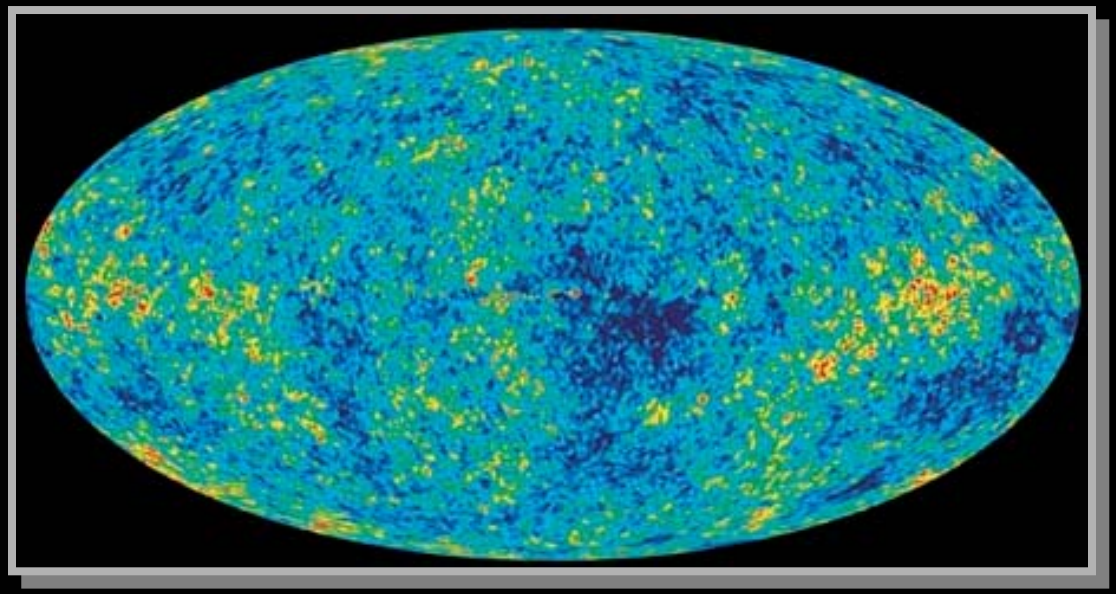
(Hawking radiation)



Imperfections are beautiful!



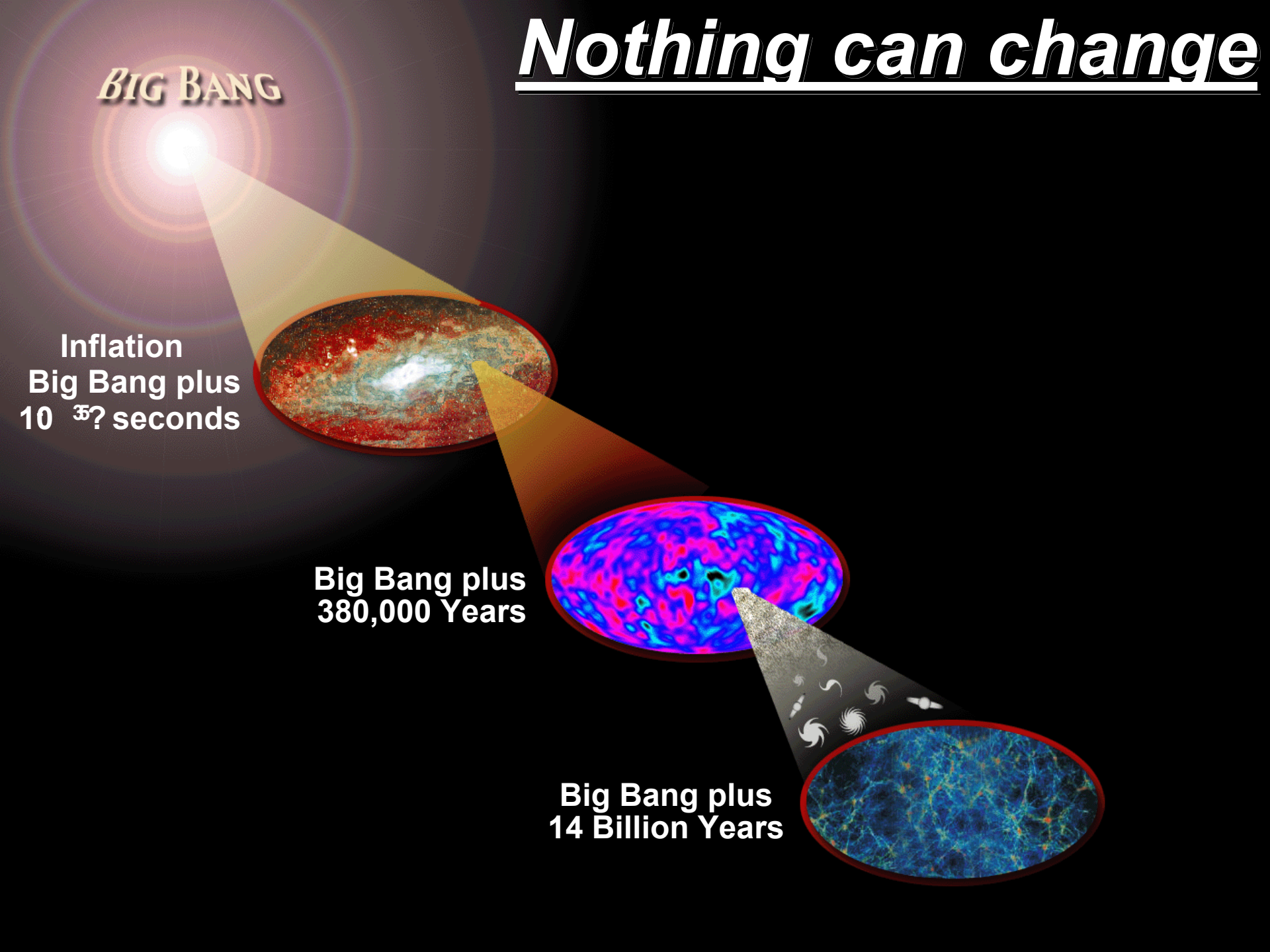
Tethys
90 minutes ago



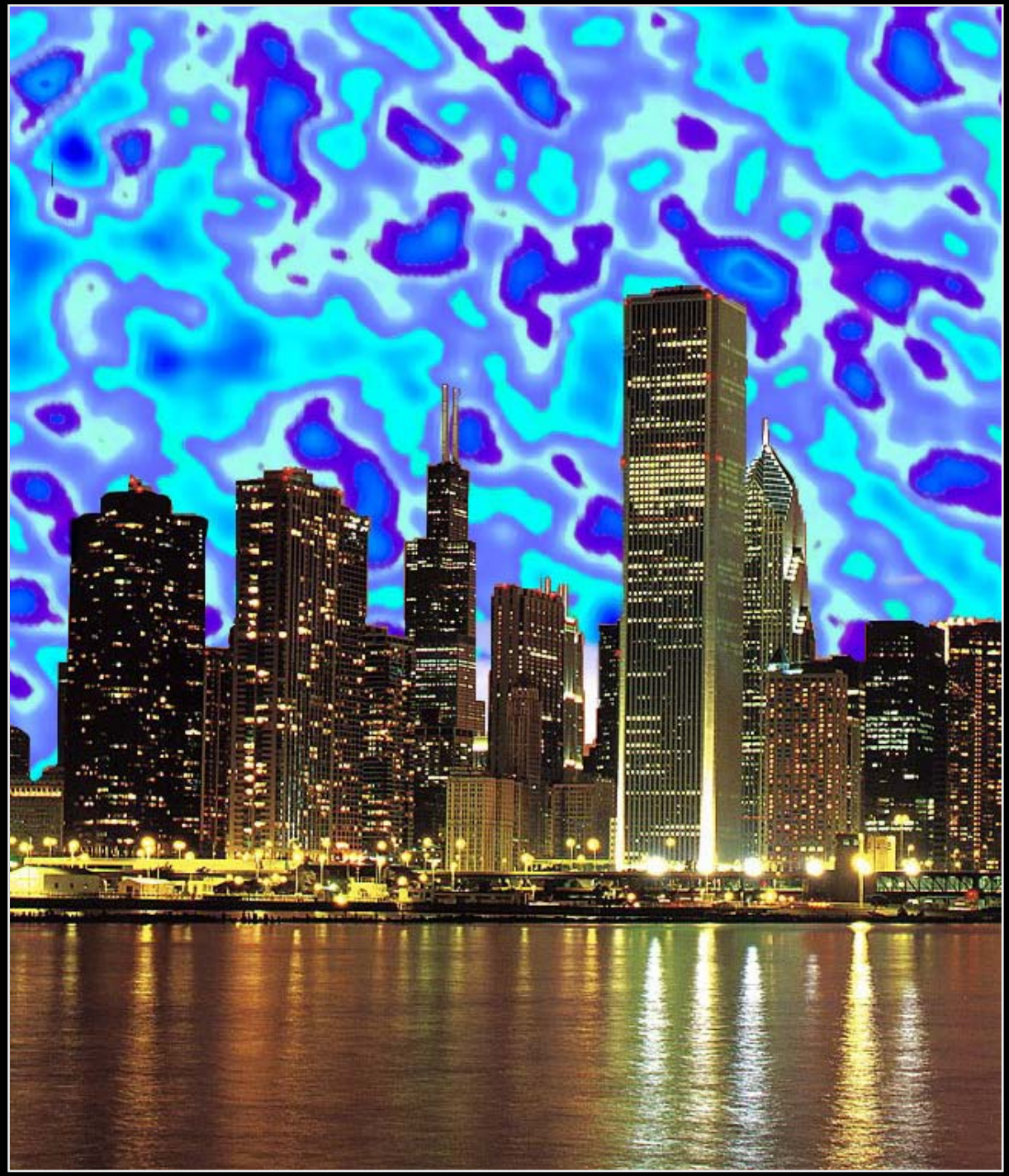
The universe
13.78 billion - 380,000 years ago

The wrinkles tell a story!

Nothing can change



A pattern
of
vacuum
quantum
fluctuations



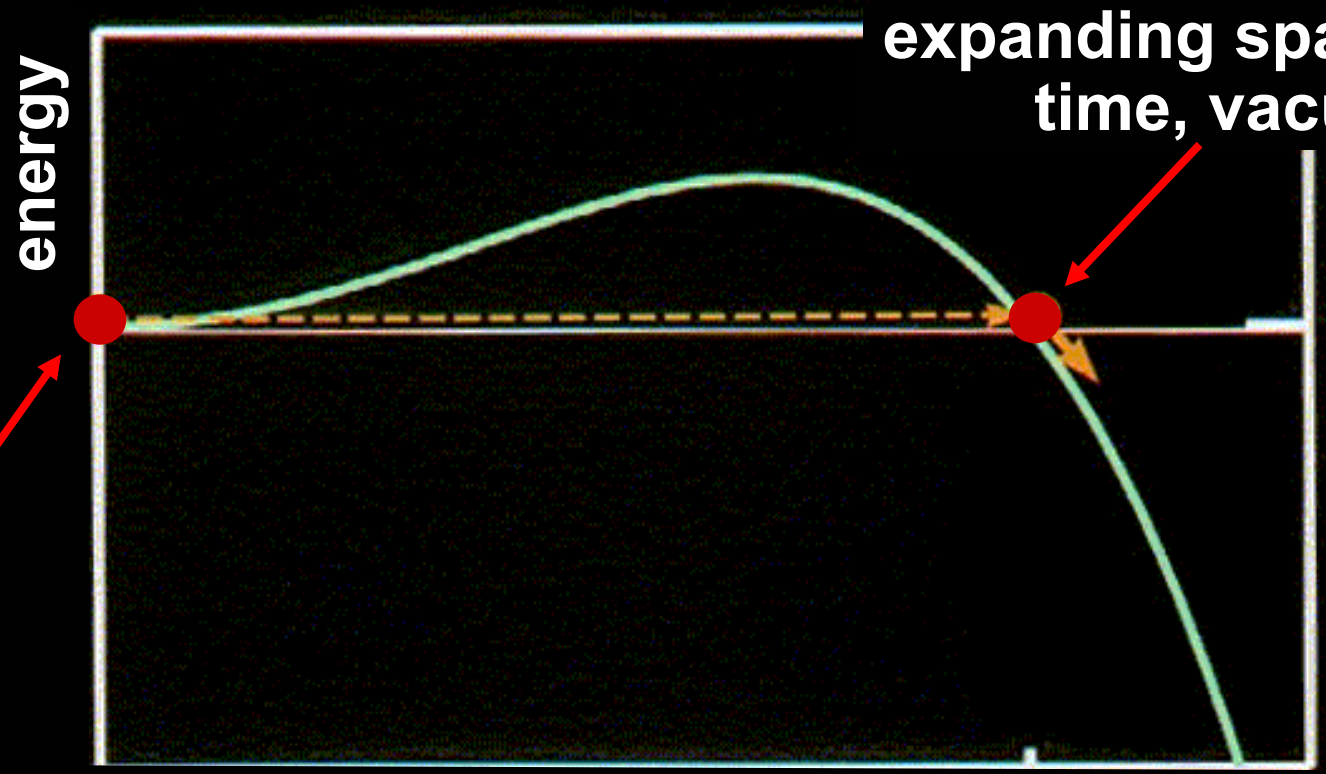
Before nothing?

THE UNIVERSE HAD A BEGINNING:

quantum creation of space, time, vacuum *from less than nothing.*

nothing is unstable -- emergence of the universe is *inevitable.*

Quantum tunneling

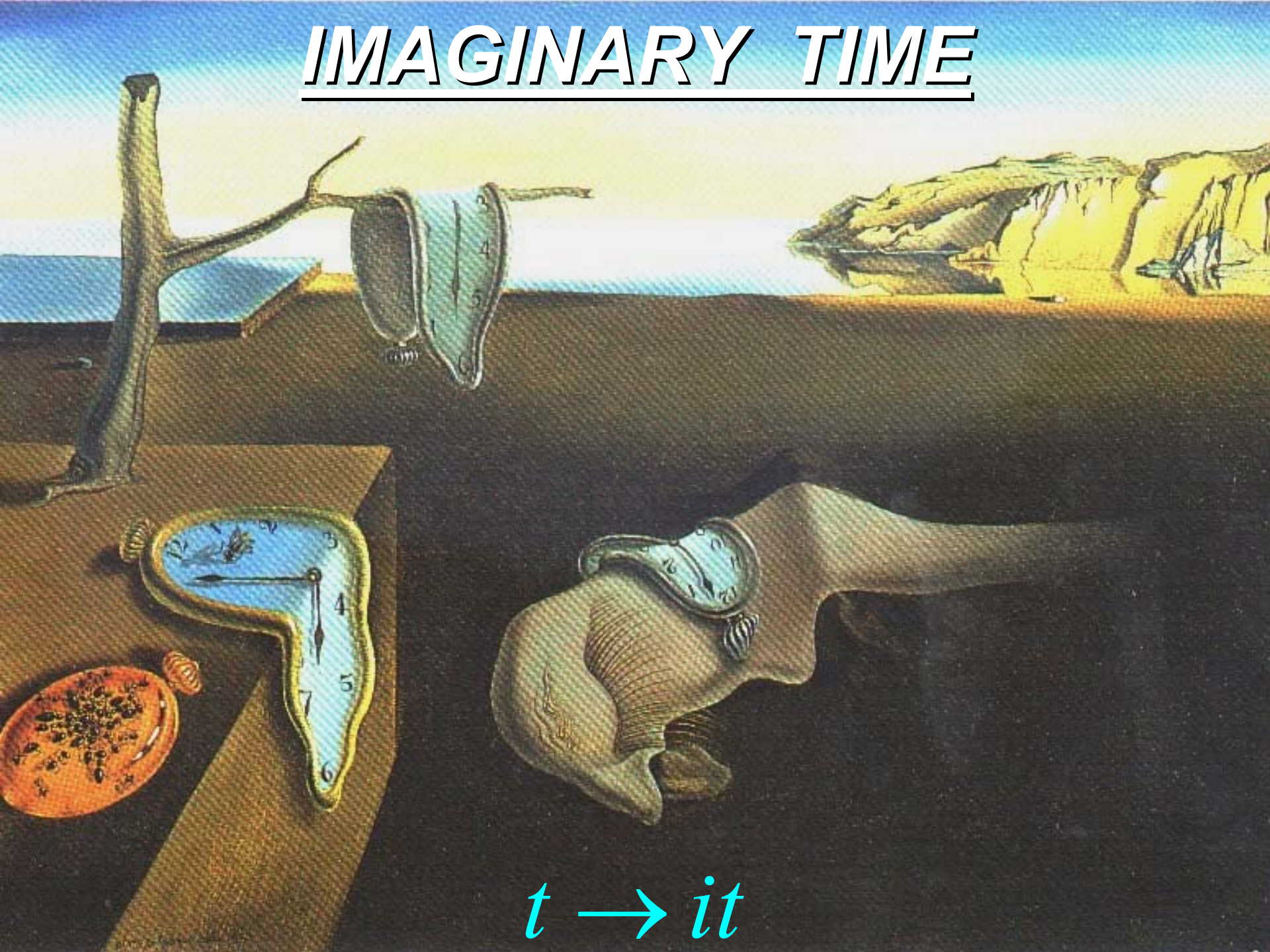


NO

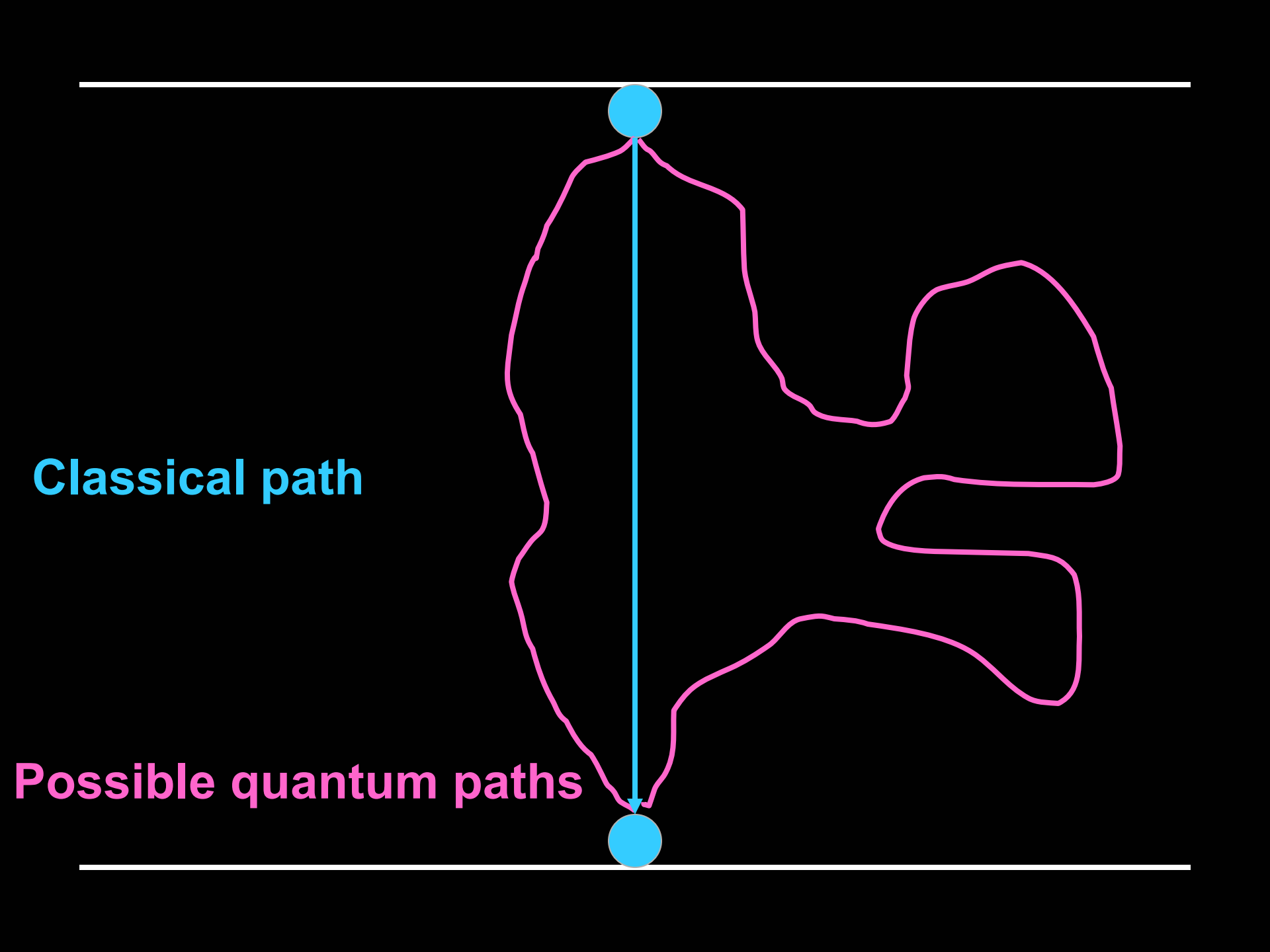
...space
...time
...vacuum
...soup

Motion in
“IMAGINARY TIME”

IMAGINARY TIME



$$t \rightarrow it$$


Classical path
Possible quantum paths

Before nothing?

THE UNIVERSE HAD A BEGINNING:

quantum creation of space, time, vacuum *from less than nothing.*

nothing is unstable -- emergence of the universe is *inevitable.*

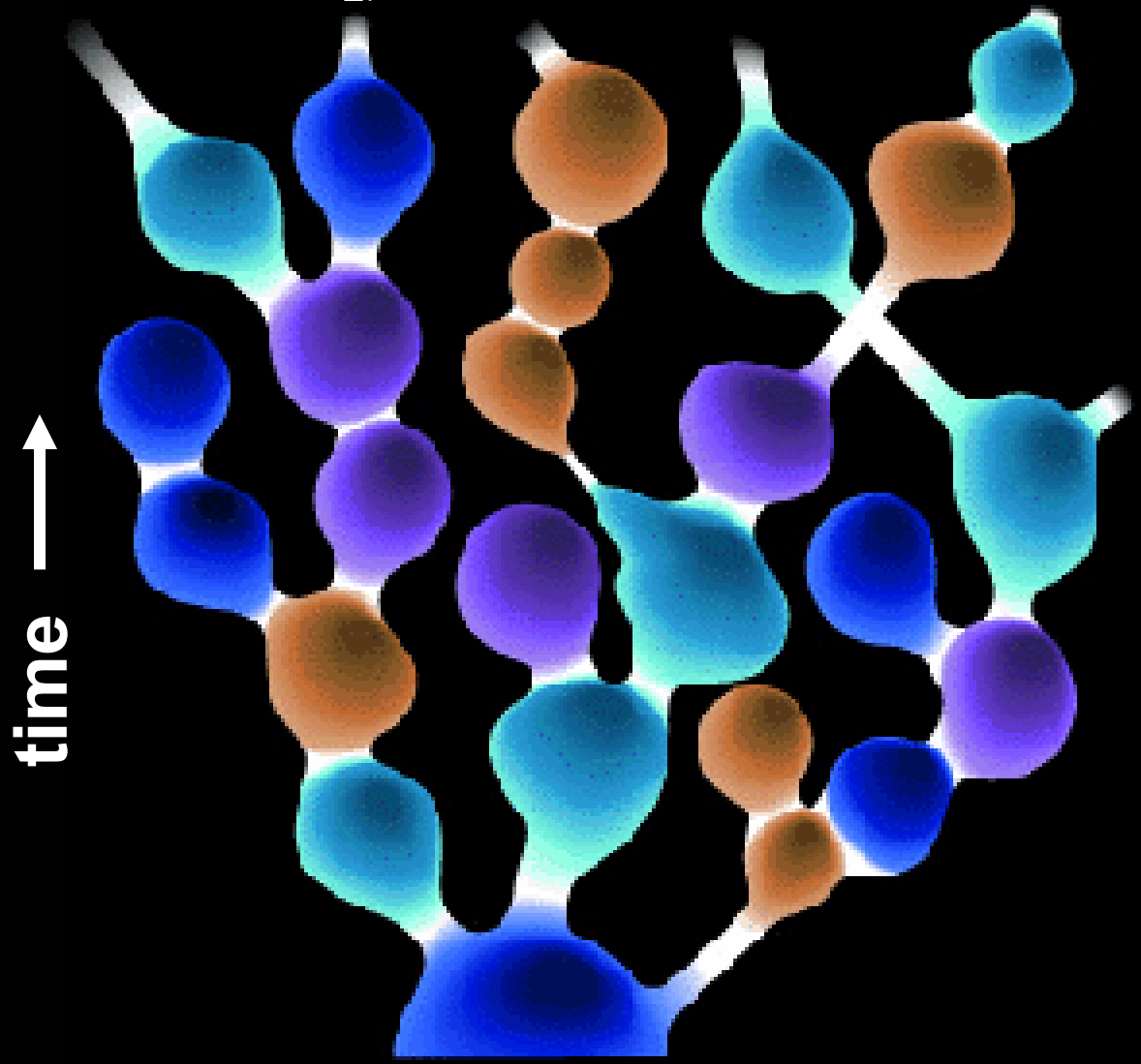
THE UNIVERSE IS ETERNAL:

universe is *still inflating.*

on largest scales, universe is unchanging -- *no beginning and no end.*

Quantum fluctuations lead to many different bubbles

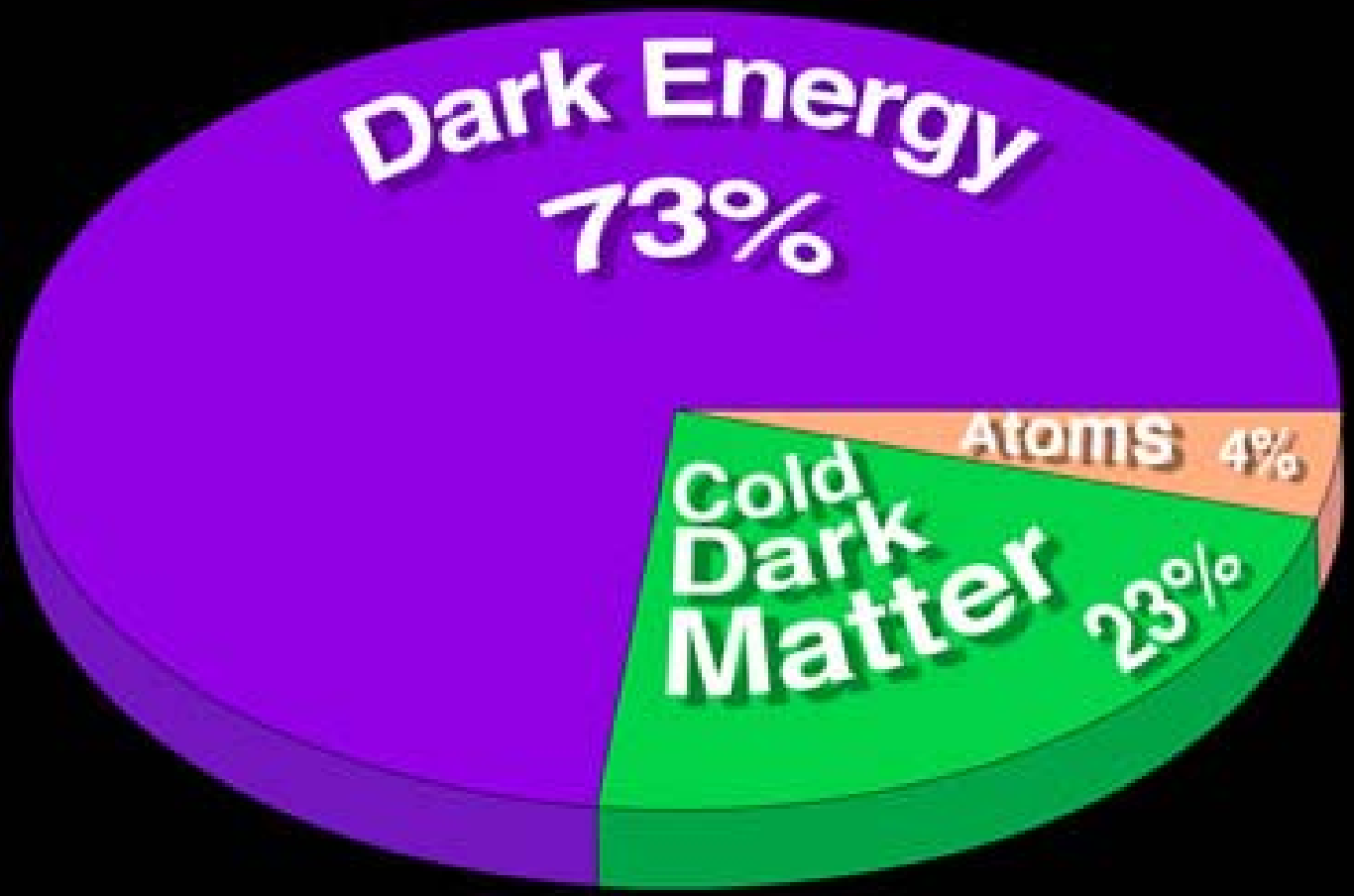
Eternally self-reproducing universe



Universe has no beginning….no end

Each bubble grows to cosmological size

ΛCDM



Mission accomplished …

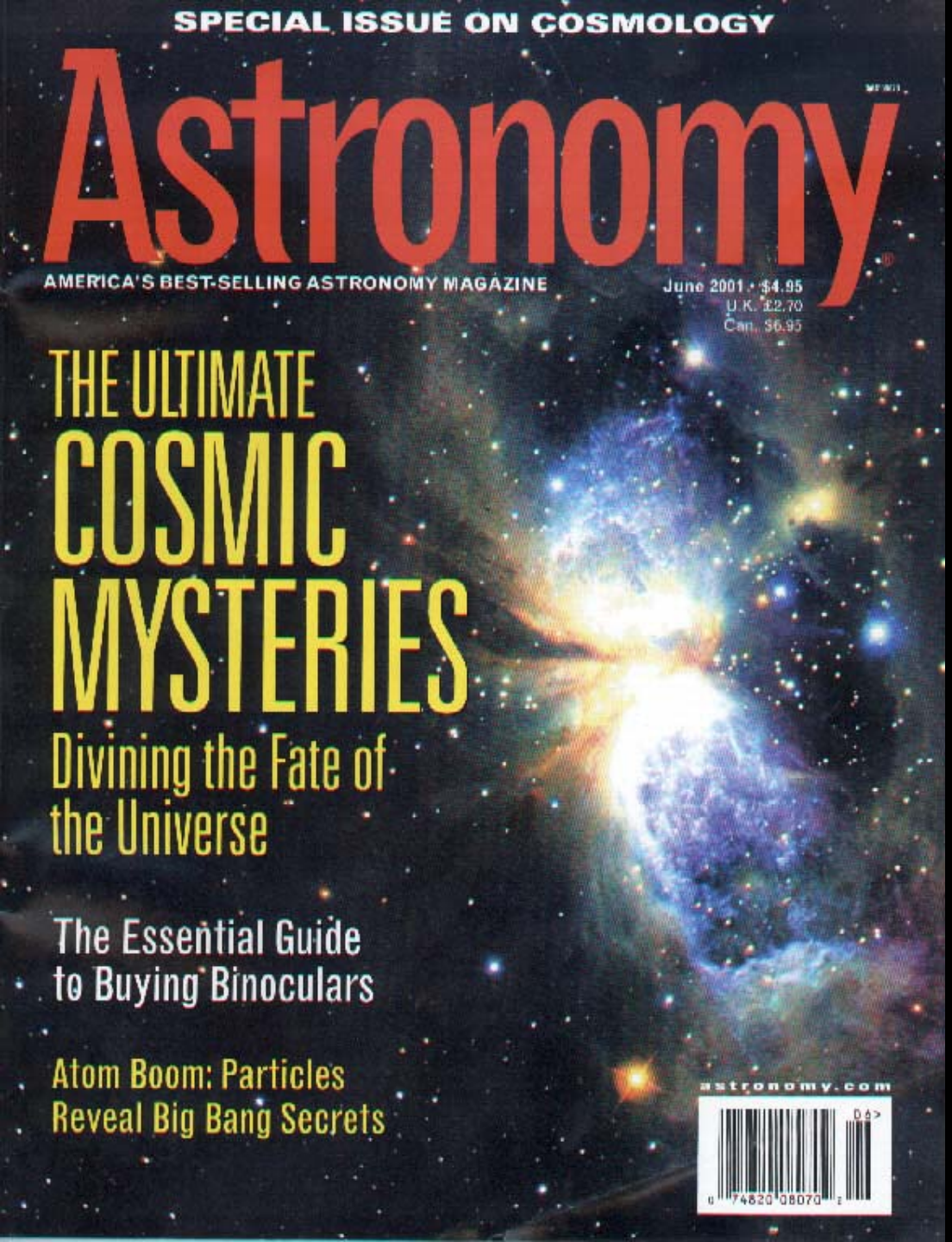
… or premature jubilation?

A standard cosmological model?*

- Radiation
- Normal matter
- Neutrinos
- Dark matter
- Dark energy
- Inflation

- Hypotheses?
- Saving the appearances?
- Epicycles?

** Do we want one? The goal is not a standard one, but a correct one!*



Cosmic Questions:

1. **How multidimensional is the universe?**

26, 12, 11, 10, 2 dimensions?

How many dimensions?

- Extra dimensions required in string theory/M-theory
  - *D = 26*, 12, *11, or 10*
  - What to do with the extra dimensions?

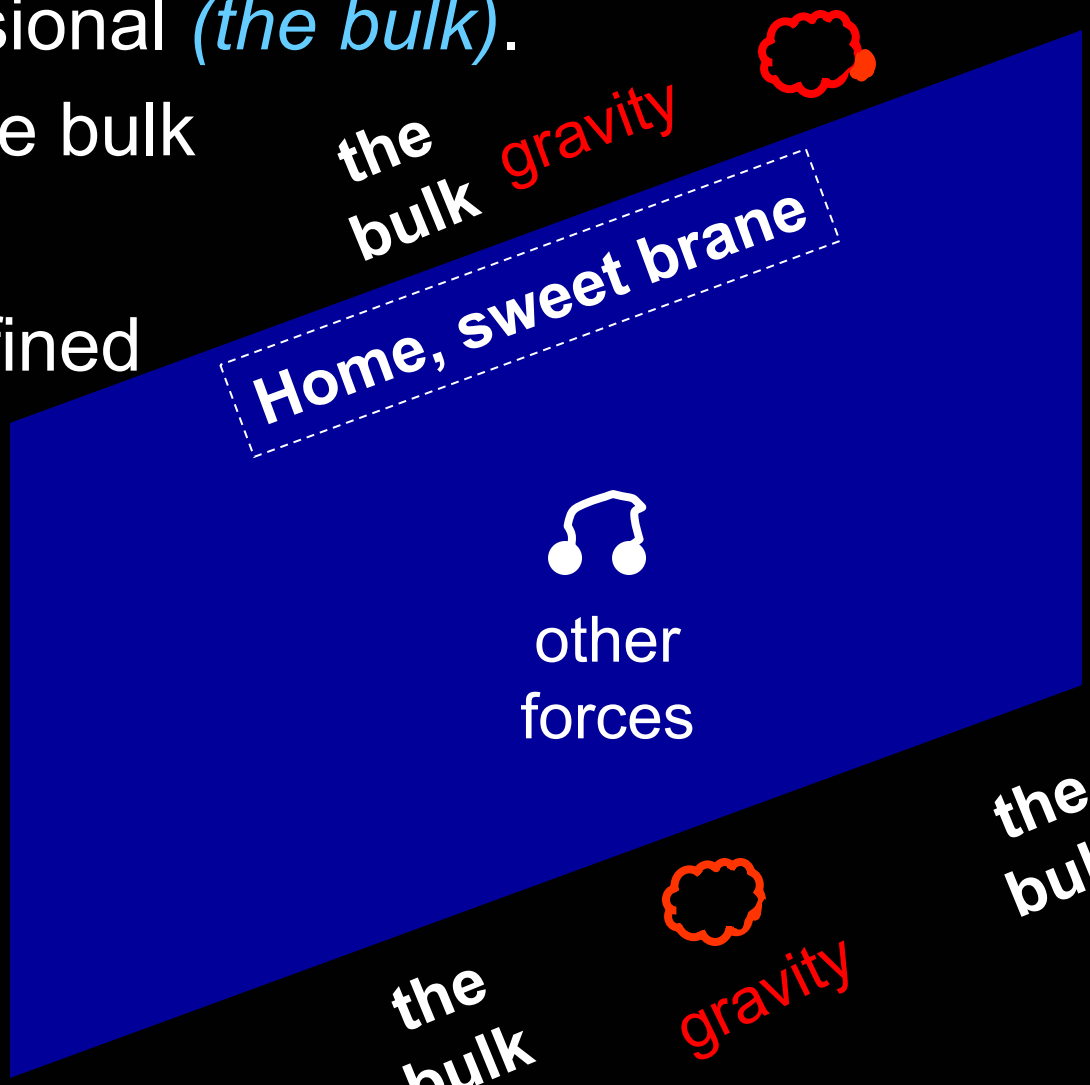
- Old idea of extra dimensions and unification

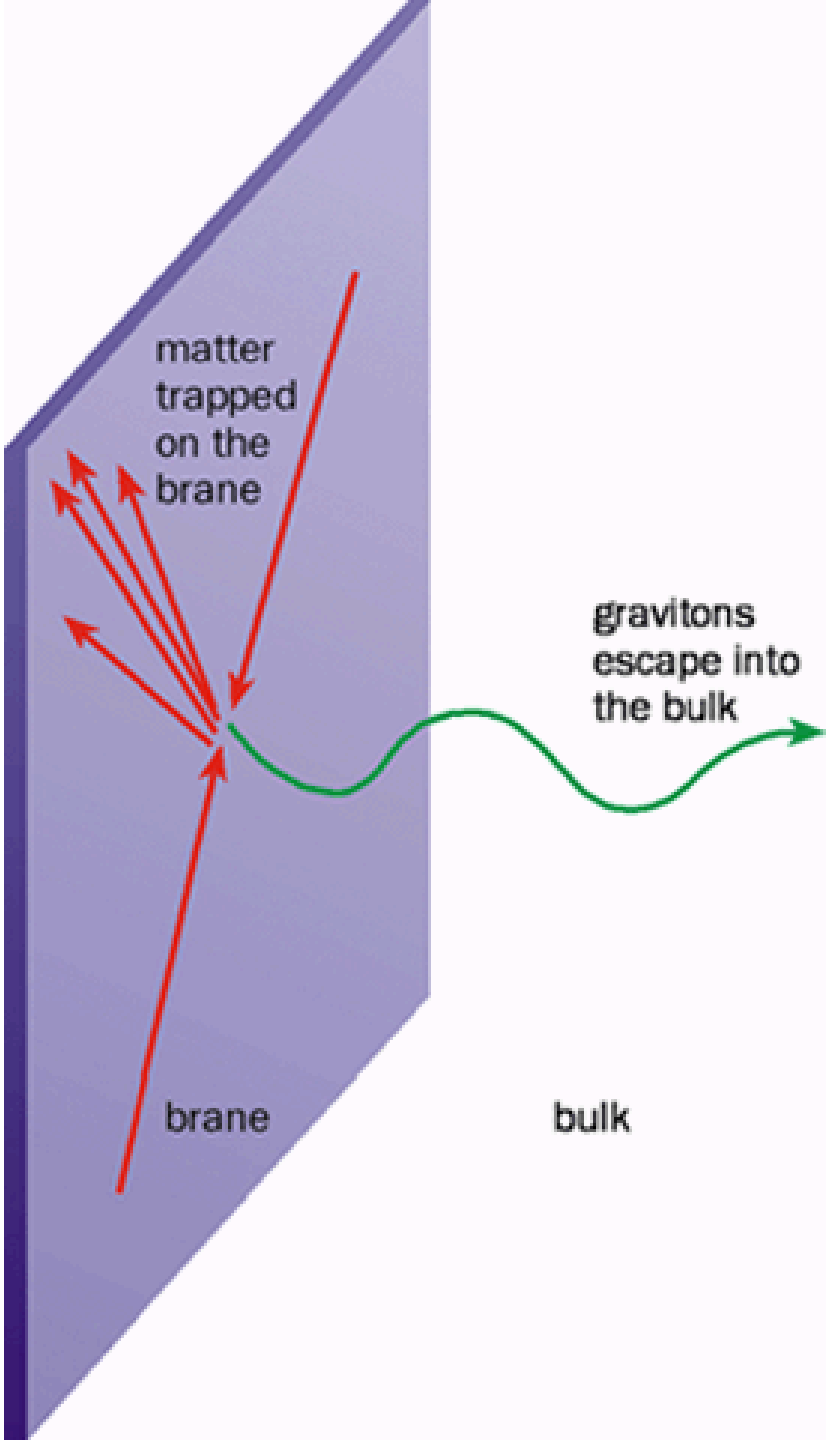
  Kaluza (1919) Klein (1926)
  - "Compact" extra dimension

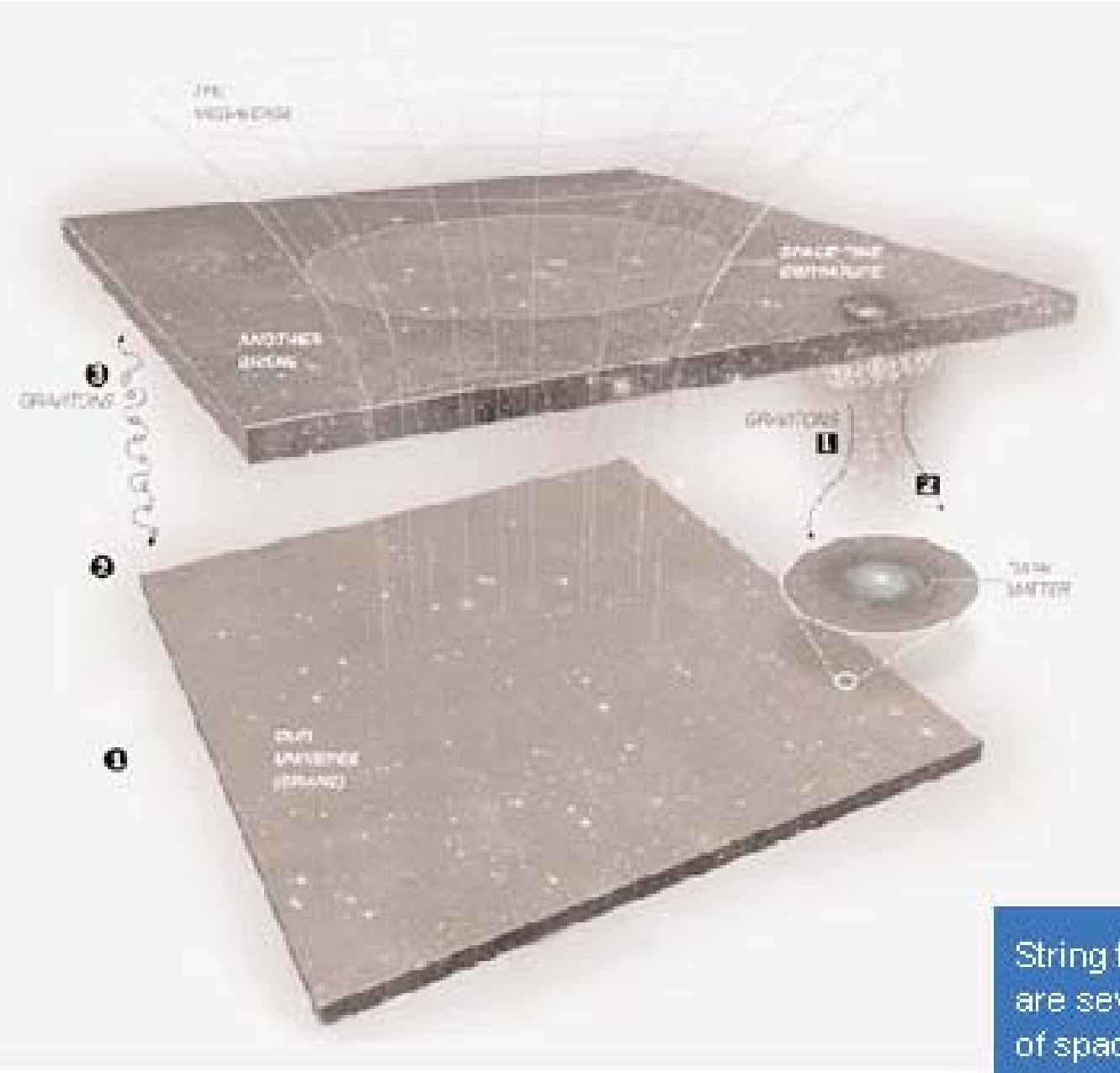
  - unify gravitational force & electromagnetic force

Brane new world

- We live on a *(3+1)*-dimensional slice *(the brane)* in a *(3+1+n)*-dimensional *(the bulk)*.
  - Gravity lives in the bulk (closed strings)
  - Other forces confined to the brane (open strings)



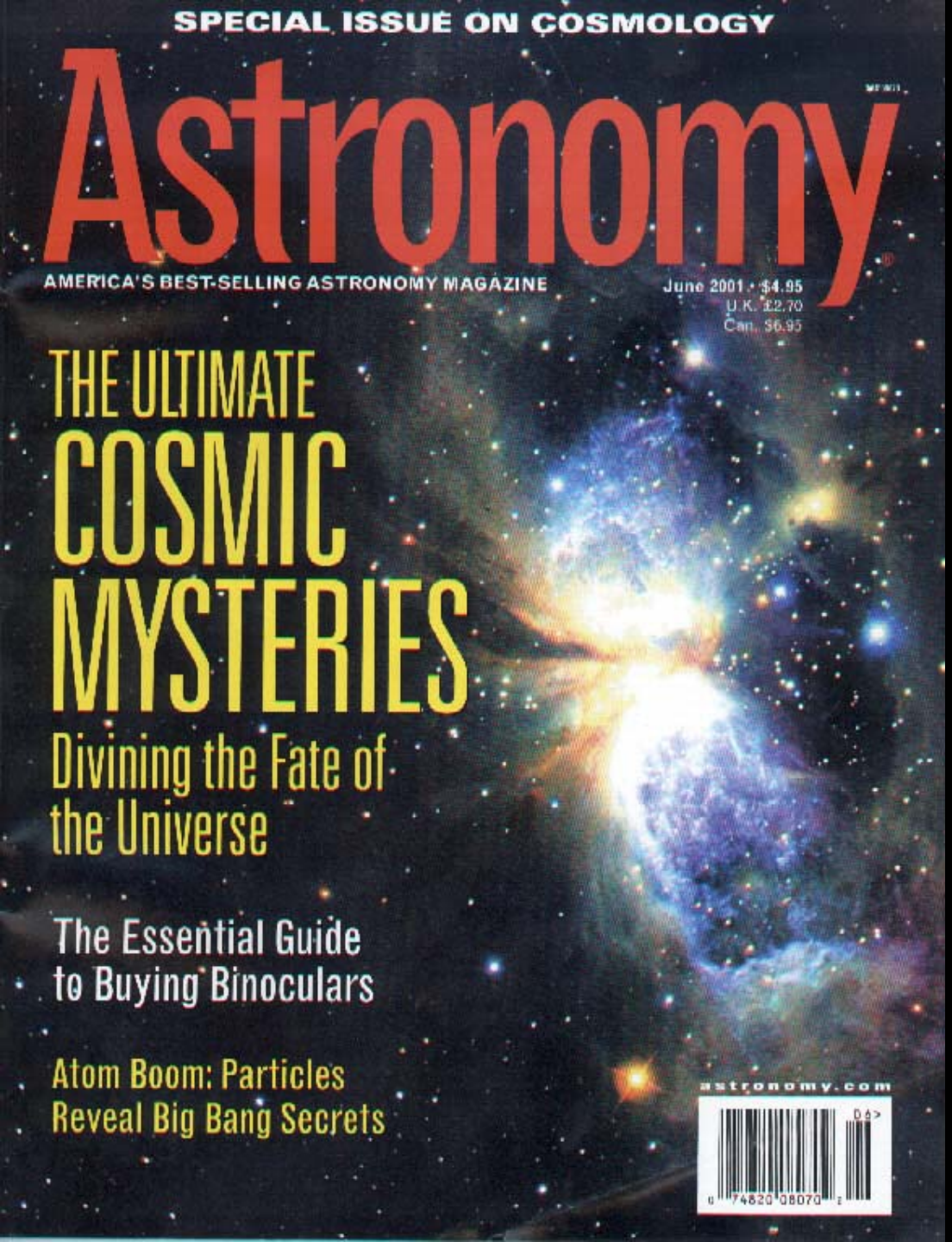

matter
trapped
on the
brane
gravitons
escape into
the bulk
brane
bulk



"The imagination is one of the forces of nature."

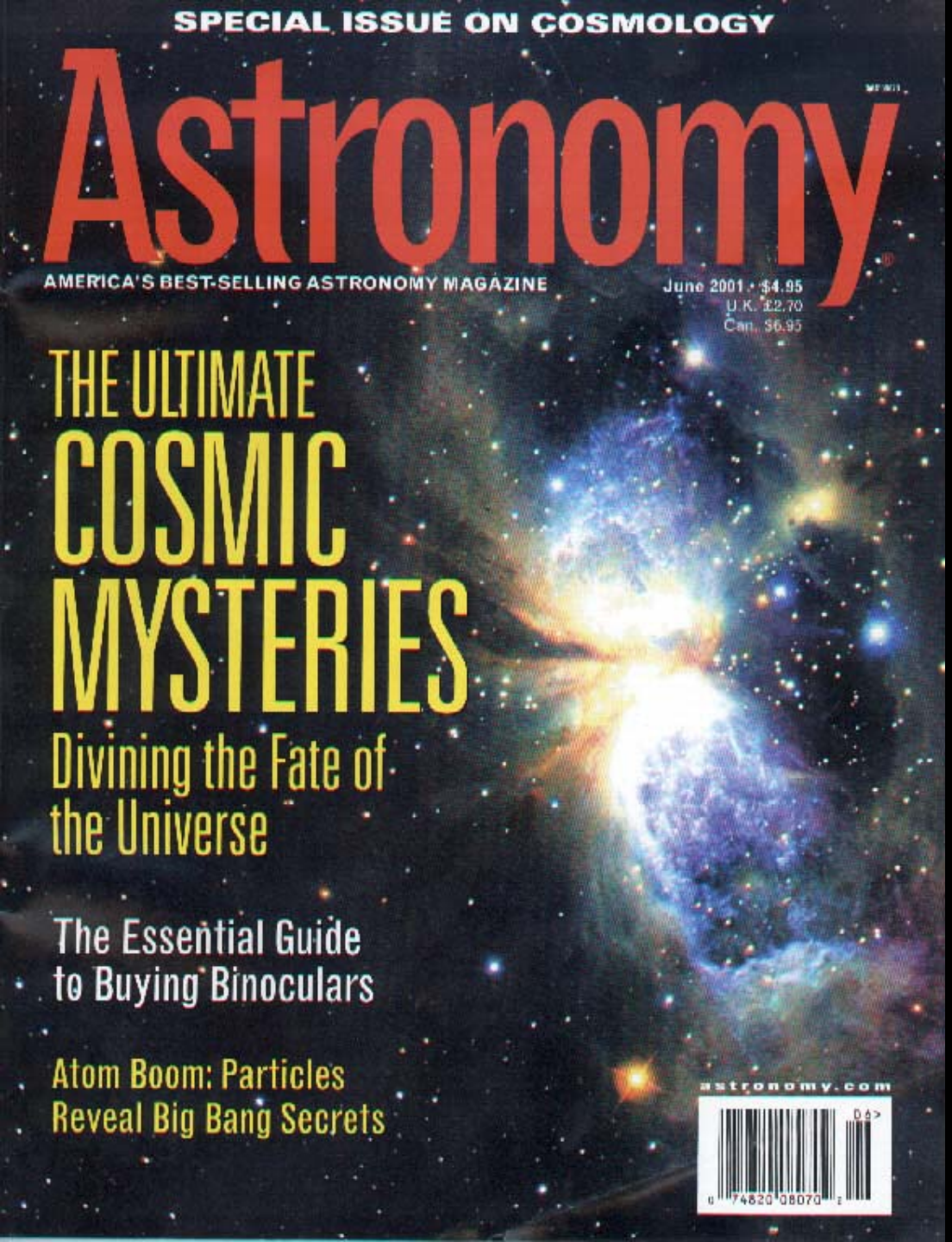
—*Wallace Stevens*

String theory predicts there are seven extra dimensions of space waiting to be discovered.



Cosmic Questions:

1. **How multidimensional is the universe?**
2. **How did the universe begin?**



Cosmic Questions:

1. How multidimensional is the universe?
2. How did the universe begin?
3. Why does matter fill the universe?

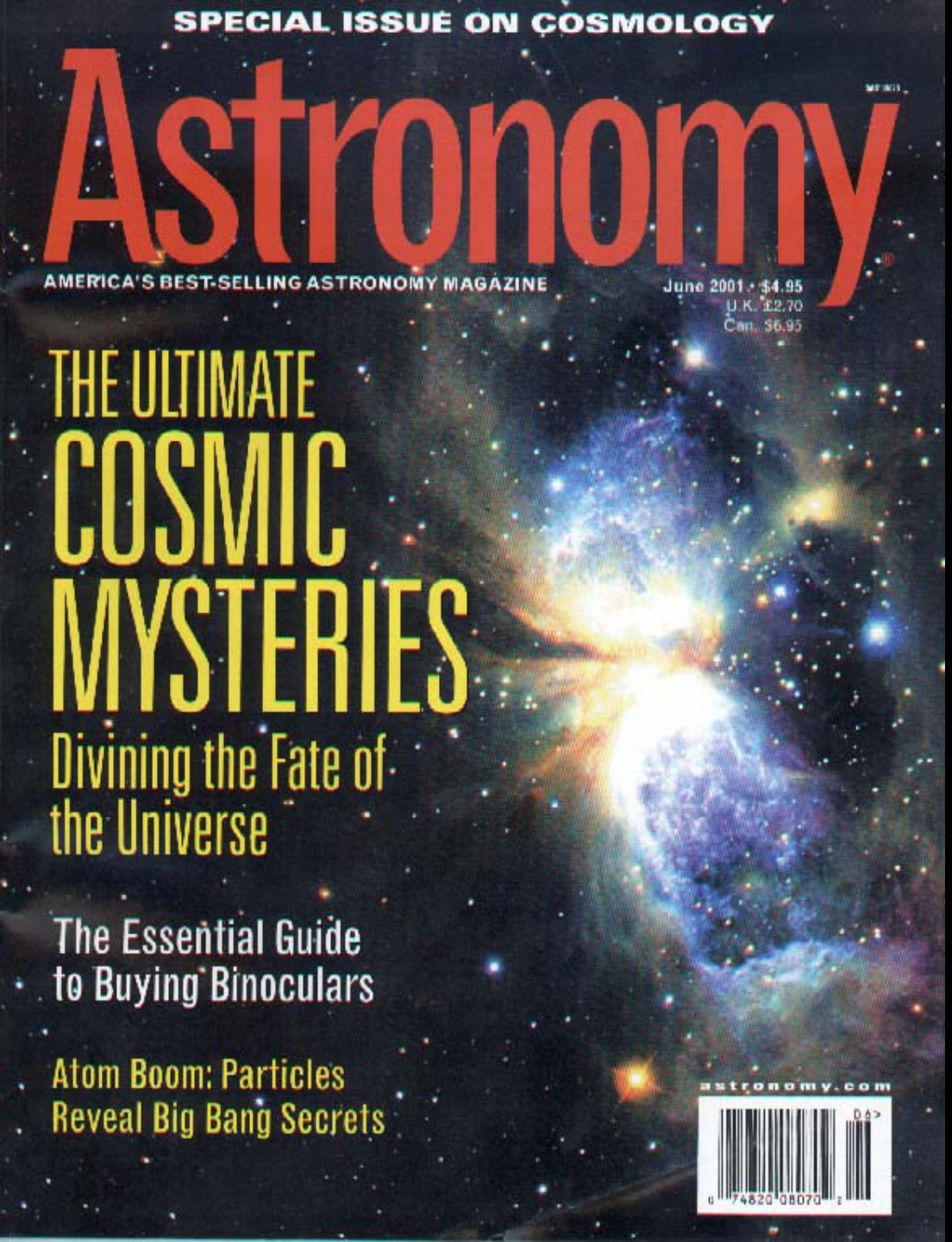
An average cubic meter of the universe today:

400,000,000	photons
1	protons or neutrons
0	antiprotons or antineutrons

Hot and asymmetric universe

An average cubic meter of the early universe:

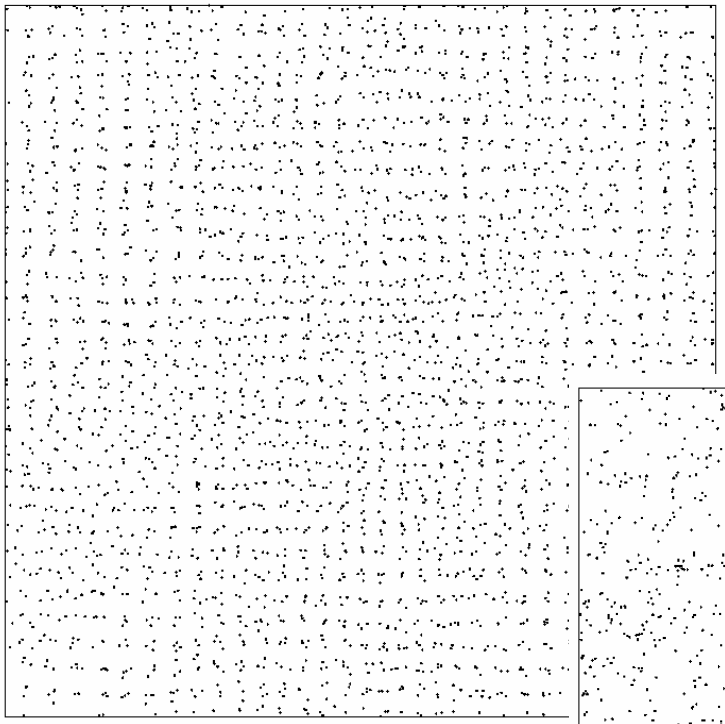
400,000,000	photons
400,000,000	protons or neutrons
399,999,999	antiprotons or antineutrons

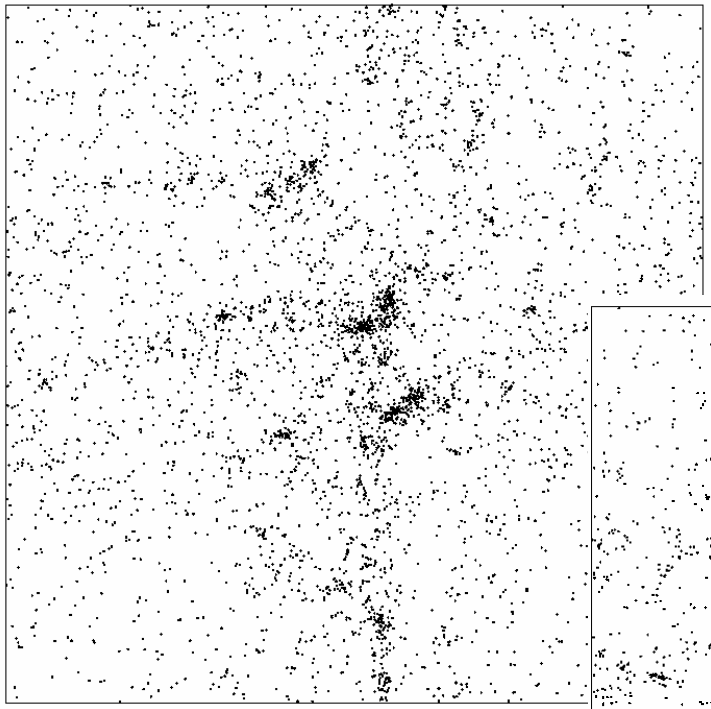


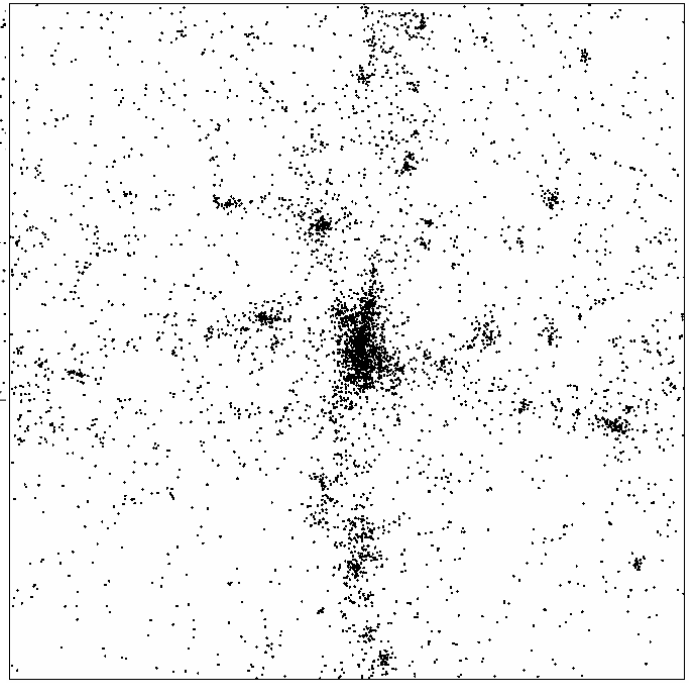
Cosmic Questions:

1. How multidimensional is the universe?
2. How did the universe begin?
3. Why does matter fill the universe?
4. How did galaxies form?

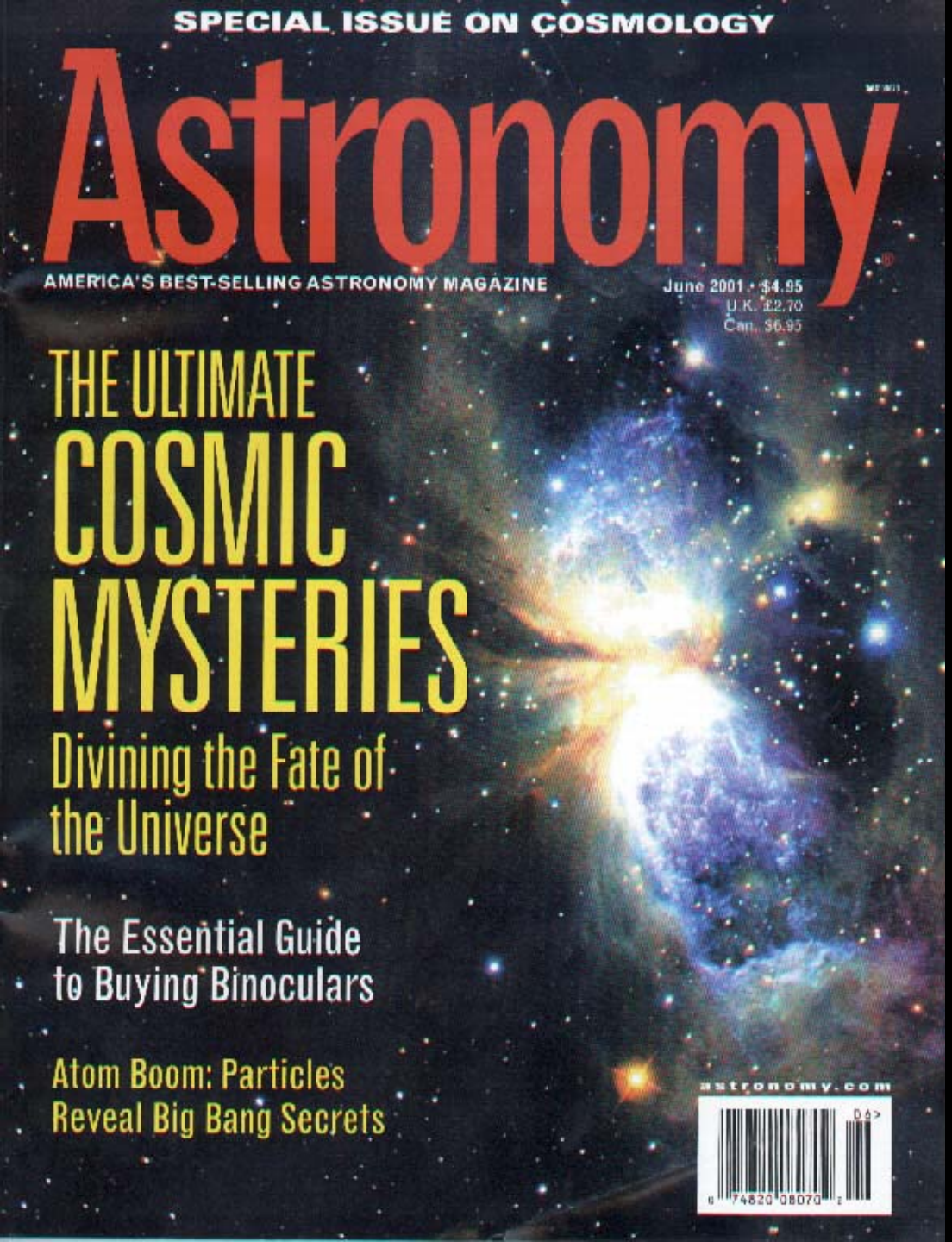
Seeds of structure







time



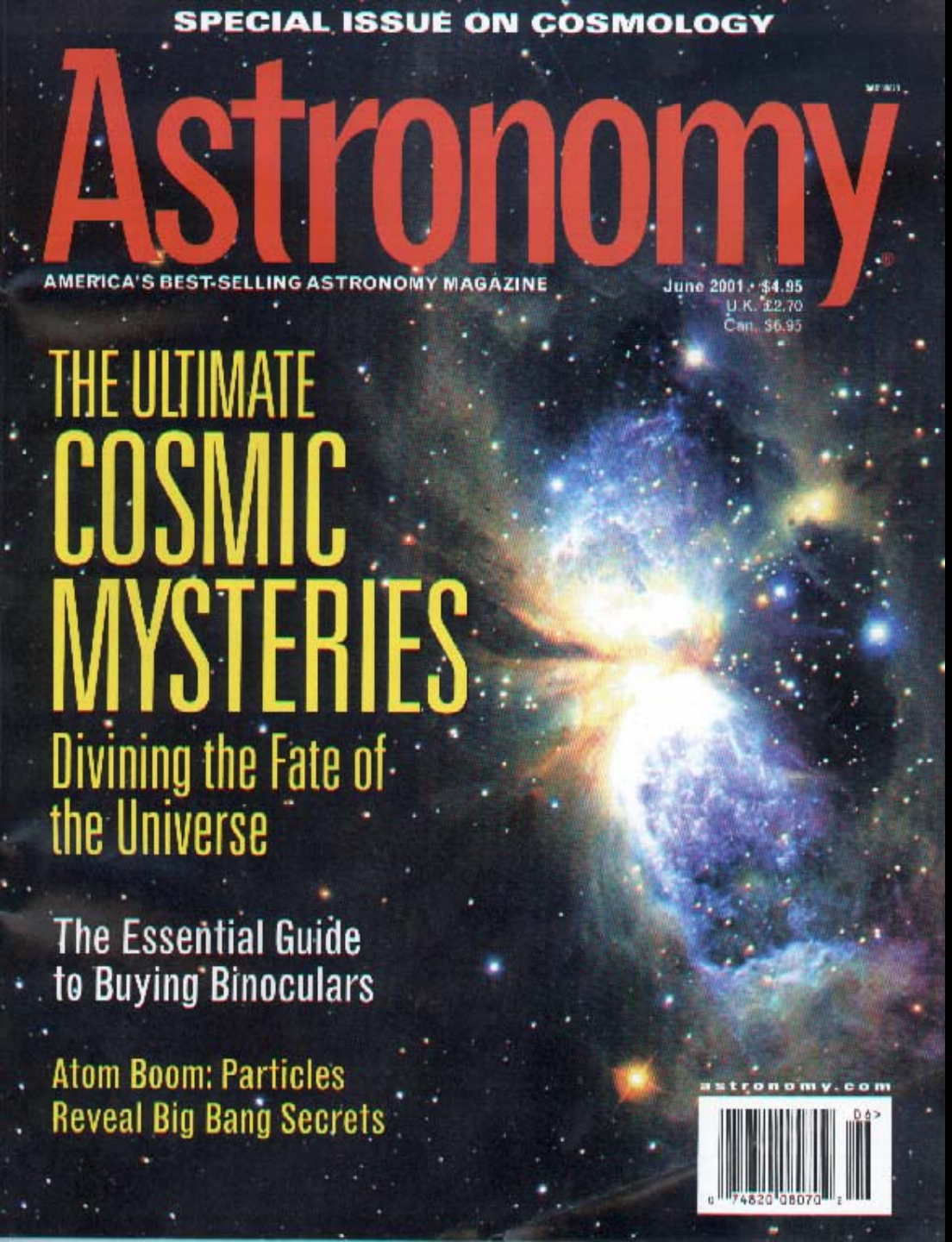
Cosmic Questions:

1. How multidimensional is the universe?
2. How did the universe begin?
3. Why does matter fill the universe?
4. How did galaxies form?
5. What is cold dark matter?

Most of the universe is dark !

- Modified Newtonian dynamics
- Planets
- Mass disadvantaged stars

  brown red white
- Black holes
- Fossil remnant of the big bang
- The weight of space



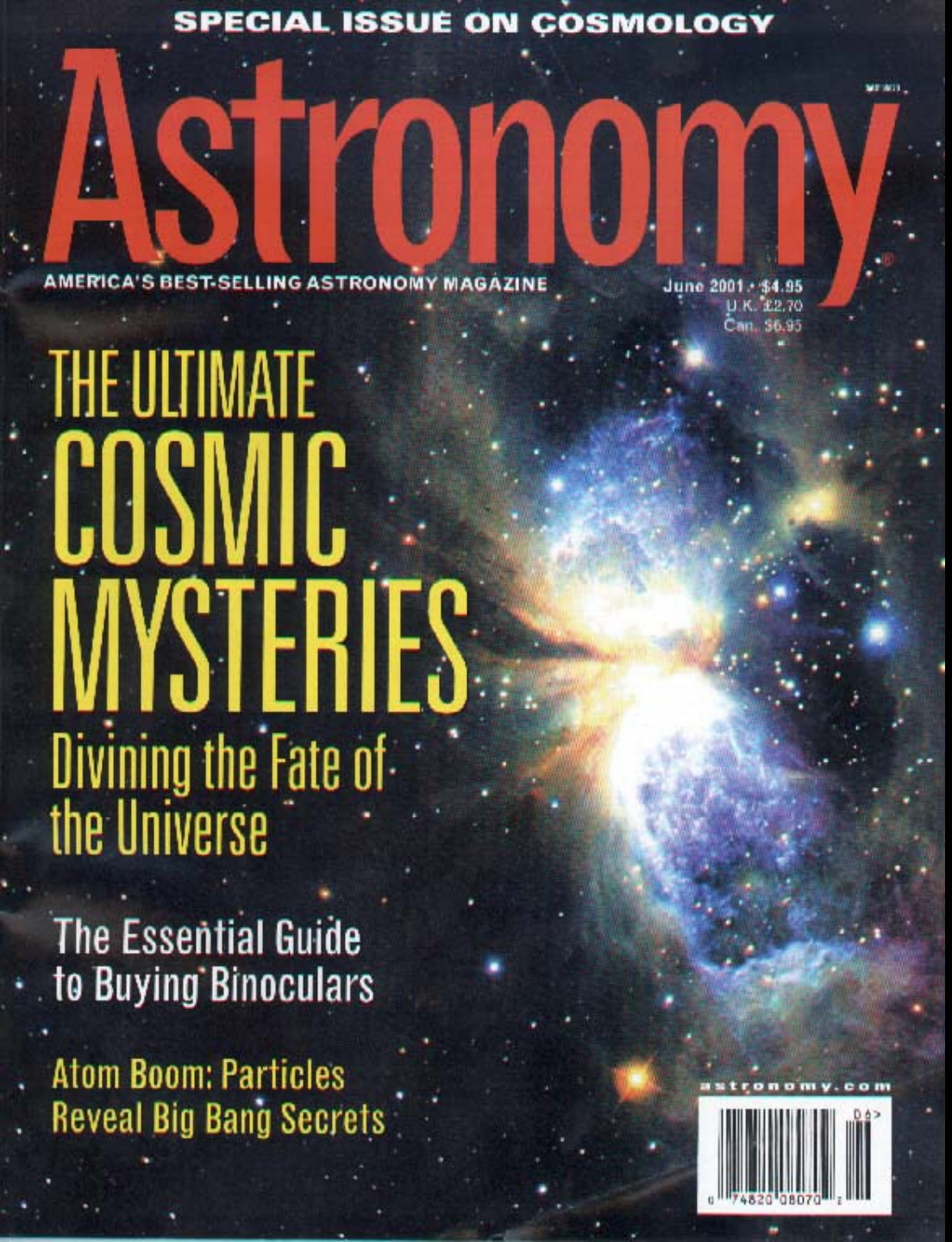
Cosmic Questions:

1. How multidimensional is the universe?
2. How did the universe begin?
3. Why does matter fill the universe?
4. How did galaxies form?
5. What is cold dark matter?
6. Are all the baryons assembled in galaxies?

Big-bang nucleosynthesis tells us the present baryon density

We only see 10% of that – most of normal matter is dark

Simulations predict it is in hot (million degrees) gas between galaxies.



Cosmic Questions:

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6. Are all the baryons assembled in galaxies?
7. What is the dark energy?

Energy of the quantum vacuum

Observed: $\rho \leq 10^{-30}$ g cm^{-3}

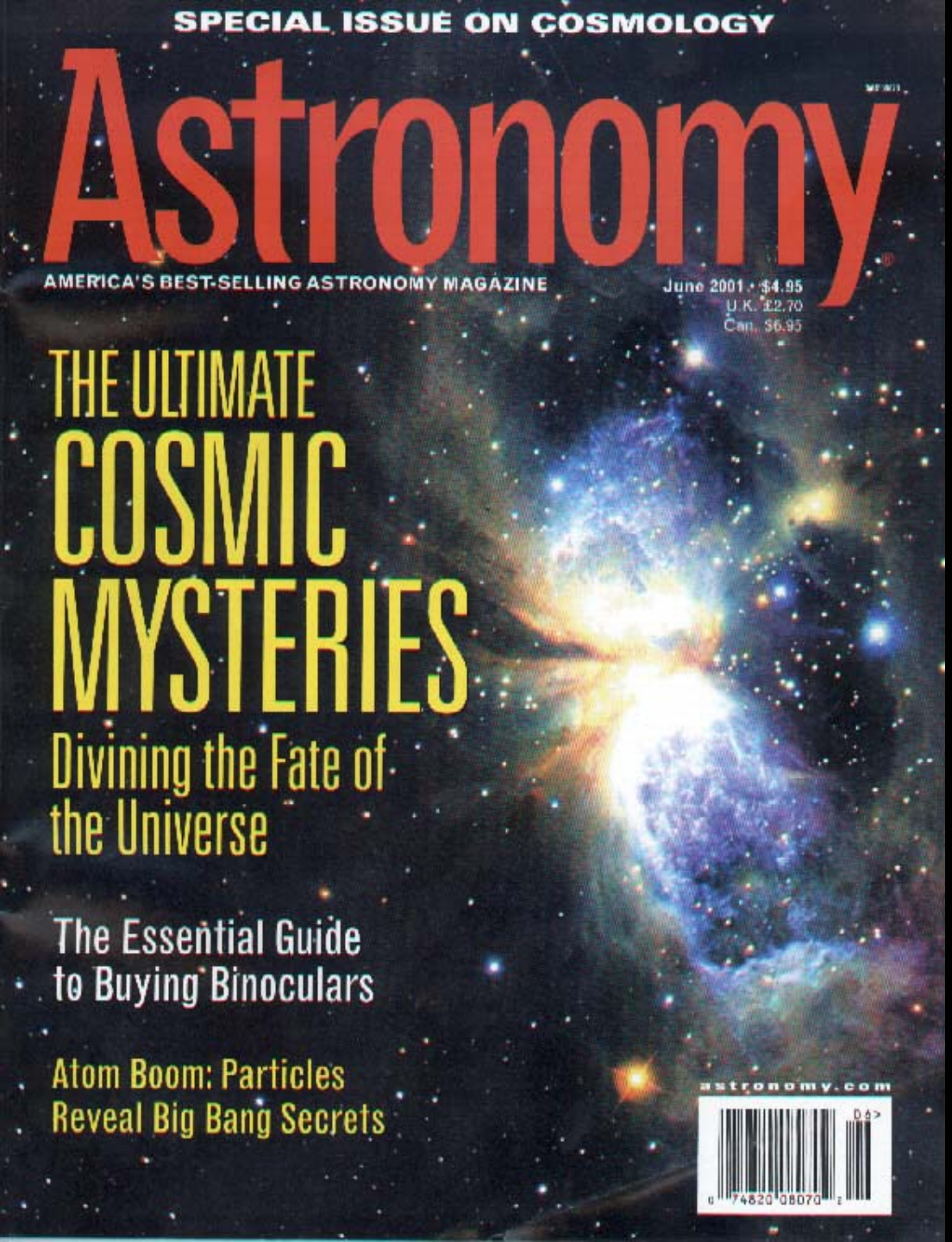
Quantum field theory: $\rho = \infty$ g cm^{-3}

Quantum gravity: $\rho = 10^{+90}$ g cm^{-3}

Supersymmetry: $\rho \leq 10^{+30}$ g cm^{-3}

Higgs potential: $\rho \sim -10^{+25}$ g cm^{-3}

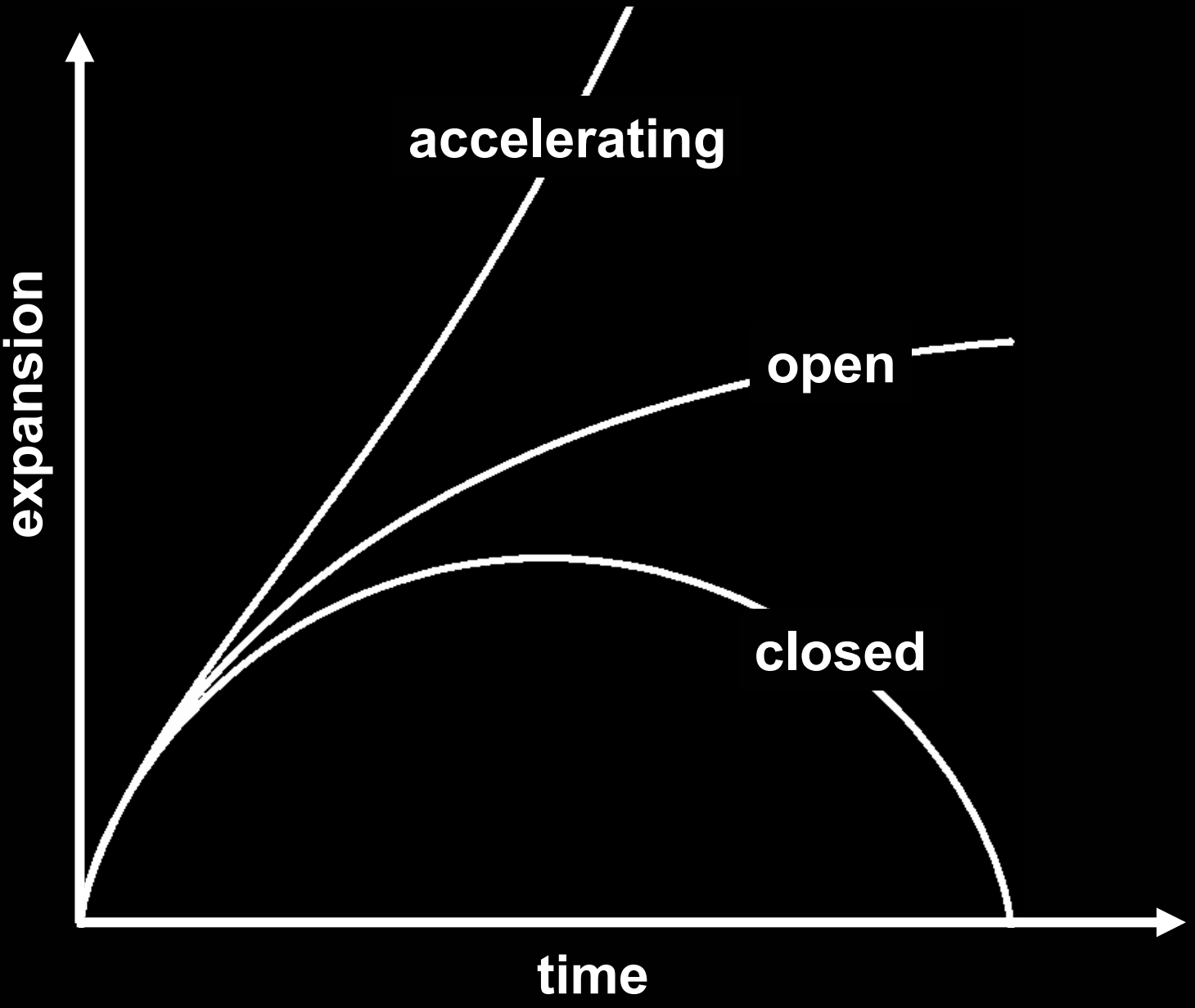
Other sources: $\rho \sim \pm 10^{+20}$ g cm^{-3}

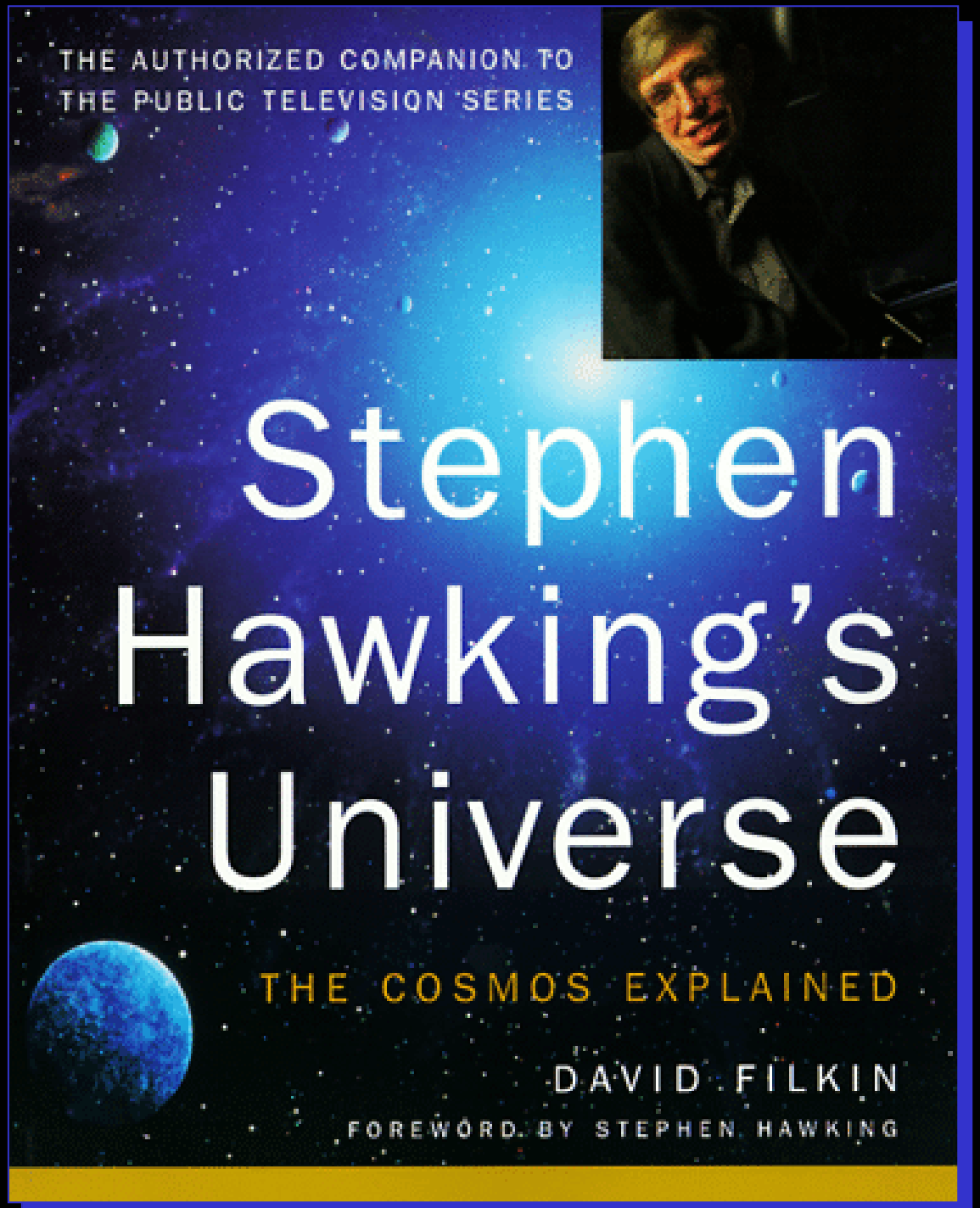


Cosmic Questions:

1. How multidimensional is the universe?
2. How did the universe begin?
3. Why does matter fill the universe?
4. How did galaxies form?
5. What is cold dark matter?
6. Are all the baryons assembled in galaxies?
7. What is the dark energy?
8. What is the destiny of the universe?

The accelerating universe?





It's your universe too!